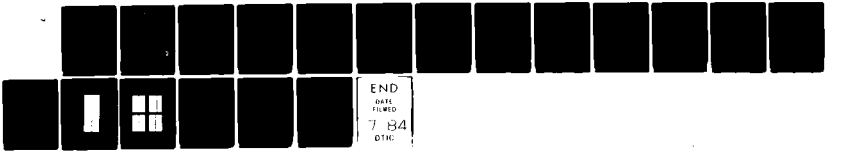
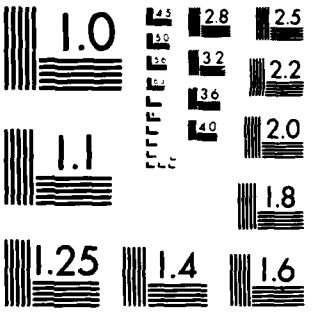
AD-A141 874 PULSED-LASER GENERATION OF ULTRA-SHORT ACOUSTIC PULSES: 1/1
APPLICATION FOR T..(U) IBM RESEARCH LAB SAN JOSE CA
A C TAM 18 MAY 84 RJ-4306 N00014-83-C-0170

UNCLASSIFIED F/G 20/1 NL



END
DATE FILMED
7 84
DTIC



RJ 4306 (47134) 5/18/84
Physics

(12)

Research Report

PULSED-LASER GENERATION OF ULTRA-SHORT ACOUSTIC PULSES: APPLICATION FOR THIN-FILM ULTRASONIC MEASUREMENTS

A. C. Tam

IBM Research Laboratory
San Jose, California 95193

IBM Research Division
Yorktown Heights, New York • San Jose, California • Zurich, Switzerland

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: 8	2. GOVT ACCESSION NO.: AD-A141 874	3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): Pulsed-Laser Generation of Ultra-Short Acoustic Pulses: Application of Thin-Film Ultrasonic Measurements		5. TYPE OF REPORT & PERIOD COVERED: Technical Report 6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): A. C. Tam		8. CONTRACT OR GRANT NUMBER(s): N00014-83-C-0170
9. PERFORMING ORGANIZATION NAME AND ADDRESS: International Business Machines Corp. 5600 Cottle Road San Jose, CA 95193		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 633-844
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research 800 N. Quincy Street Arlington, VA 22217		12. REPORT DATE: 5/18/84 13. NUMBER OF PAGES: 12
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report): Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release and sale; its distribution is unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Submitted for publication in Applied Physics Letters

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Laser applications, Opto acoustics, photoacoustics, ultrasonics, attenuation, velocity, thin-film

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We demonstrate opto-acoustic generation and detection of acoustic pulses of 1 nanosecond duration in condensed matter. Such opto-acoustic pulses are at least one order of magnitude shorter than those previously reported. These narrow acoustic pulses find new application for thin-film pulse measurements which are not possible with conventional transducer techniques. Round trip echo times are measured to 1% accuracy for stainless steel films of 12 micron thickness. This provides a new high accuracy thickness measurement in a pulsed mode. Ultrasonic attenuation for the narrow acoustic pulses are very large and are also measured.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

RJ 4306 (47134) 5/18/84
Physics

PULSED-LASER GENERATION OF ULTRA-SHORT ACOUSTIC PULSES: APPLICATION FOR THIN-FILM ULTRASONIC MEASUREMENTS

A. C. Tam

IBM Research Laboratory
San Jose, California 95193

ABSTRACT: We demonstrate opto-acoustic generation and detection of acoustic pulses of 1 nanosecond duration in condensed matter. Such opto-acoustic pulses are at least one order of magnitude shorter than those previously reported. These narrow acoustic pulses find new application for thin-film pulse measurements, which are not possible with conventional transducer techniques. Round trip echo times are measured to 1% accuracy for stainless steel films of 12 μm thickness. This provides a new high accuracy thickness measurement in a pulsed mode. Ultrasonic attenuation for the narrow acoustic pulses are very large and are also measured.

It is generally well known that pulsed lasers of short duration τ_L can be used to produce (via the opto-acoustic effect) acoustic pulses[1] of short duration τ_a. However, the shortest detected τ_a reported in the literature is[2] about 10 nsec, and other reported opto-acoustic (OA) pulses are longer despite the use of picosecond lasers.[3,4] A cause of large OA pulse width is the finite risetime of the acoustic detector. However, even with the use of a detector with negligible risetime, Sullivan and Tam[5] has shown that τ_a is still limited by an acoustic transit time τ_t defined as the acoustic propagation time across the OA source of length ℓ *in the direction of observation*. The investigation of Sullivan and Tam[5] indicates that

$$\tau_a \approx \left[\tau_L^2 + \tau_t^2\right]^{1/2} . \qquad (1)$$

Thus, even with the use of ultrafast detectors, short τ_a can only be obtained with short τ_L *and* τ_t. For optical excitation of a highly opaque solid (or liquid), ℓ is equal to the optical attenuation length for an end-on measurement (*i.e.*, normal to the solid surface); in this case, if $\ell \approx 10^{-5}$ cm (for highly opaque sample), and c=velocity of sound $\approx 10^6$ cm/sec, $\tau_t \approx 10^{-11}$ sec is obtained, which means that τ_a on the order of 10 picoseconds can be achieved in principle for sufficiently short τ_L. In practice, factors like large attenuation, detector rise time, surface roughness, and so on, may make the detection of very narrow acoustic pulses difficult.

This paper describes a first attempt in the generation of ultra-short acoustic pulses in solids, with $\tau_a \approx 1$ nsec, which is presently limited by the laser pulse duration, detector risetime and sample surface roughness. Such narrow acoustic pulses with highly reproducible lineshapes are ideally suitable for measuring the properties of thin films like thickness d, or acoustic velocity c and attenuation α. c and α are highly

correlated with physical properties of the film like porosity,[6] strain,[7] grain size,[8] microstructure, [9] and field distribution.[10] We demonstrate our technique on stainless steel films of thickness d as small as 12 μm, which is measured to 1% accuracy by our pulsed technique. In comparison, conventional ultrasonic pulsed echo techniques based on the use of transducers are not well suited[11] for d<100 μm because of the much longer ultrasonic pulse duration achievable.

Our experimental arrangement to demonstrate the generation and detection of OA pulses with $\tau_a \approx 1$ nsec is indicated in Fig. 1. The pulsed excitation source is an atmospheric-pressure N_2 laser (PRA model LN1000) producing laser pulses at 337 nm of duration $\tau_L = 0.5$ nsec, and energy E=1.5 mJ. The laser beam is weakly focused to a spot size of about 2 mm×0.5 mm on the sample, which is polished type 302 stainless steel film (Precision brand stainless steel shim from Precision Steel Warehouse, Inc., Downers Grove, Illinois) of thickness d ranging from 12 μm to 260 μm. The present technique is of course not limited to metal films; indeed we have made measurements on polymer films, which have much higher ultrasonic attenuation than stainless steel films. The OA pulse is detected "end-on" with the use of a transducer[12,13] coupled to the sample with a thin film of acoustic coupling material like water. The role of the acoustic coupling material is to fill the gaps (due to sample surface roughness of ~1 μm) at the contact interface between the sample and the transducer. The transducer, developed at Ginzton Laboratory, Stanford University, consists of an approximately 5 μm thick ZnO film between 1000Å thick gold electrodes; this whole structure was rf-sputtered on a polished surface of a single crystal sapphire buffer rod. The other end of the buffer rod has the shape of a truncated cone, with a flat polished surface of diameter about 2 mm. The transducer risetime τ_r is $\lesssim 1$ nsec, and our OA

pulse widths are partially limited by τ_r. The transducer output is amplified by a 30 dB-gain preamp (Trontech model W1G2H, Neptune, New Jersey) with bandwidth 5-1000 MHz, and displayed on a 500 MHz oscilloscope.

The observed OA pulses for a stainless steel film of thickness 14 ± 2 μm (as measured by a micrometer) is shown in Fig. 2. Here, the first pulse A is due to the OA pulse that directly arrives at the ZnO sensor without undergoing any multiple reflections. The full width at half-maximum of the positive-going part of pulse A is about 0.8 sec, which is slightly larger than τ_L=0.5 nsec (τ_t is negligibly small here, on the order of 10^{-11} sec). The exact shape of the pulse is also dependent on the response of the ZnO piezoelectric film. The time delay of A with respect to the laser firing is 0.892 μs and is mainly due to the length of the sapphire buffer rod. Pulses B to I in Fig. 2 are due to multiple reflections at the surfaces of the sample, with the round trip time τ_{RT} of the sample being given by the equal spacing between adjacent pulses. The value of τ_{RT} is given in Table I. It is also clear from Fig. 2 that the pulses progressively becomes broader with more reflections, *i.e.*, more distance traversed in the sample. This is because of the phenomenon of frequency-dependent absorption, whereby higher Fourier frequency components are expected to be more strongly absorbed[8,13,14] in the steel sample. Fourier frequency decomposition of each of the pulses[15] shown in Fig. 2 should provide detailed information on the ultrasonic absorption spectrum in the hundreds of MHz range. Instead of performing this detailed ultrasonic absorption spectrum measurement, we have measured the mean effective attenuation coefficient α (at the mean Fourier frequency) by plotting the heights of the pulses in Fig. 2 in a semilog plot with respect to time or propagation distance.. Diffraction effects are negligible in our data since the mean acoustic wavelength is ~20 μm and is much

smaller than the laser spot size of 2 mm×0.5 mm. The resulting average attenuation α at the average Fourier frequency is given in Table I.

The measurements for the nominally 14 μm stainless steel sample are repeated for four other thicknesses of the same material. Some results are shown in Fig. 3, and the observed round-trip time τ_{RT} and the ultrasonic amplitude attenuation coefficient α are also given in Table I.

From the measured thickness and τ_{RT} of the thickest sample shown in Table I, the ultrasonic velocity c in the stainless steel material (rolled and polished type 302 at 23°C) is found to be $5.93(6)\times10^5$ cm/sec. Using this velocity value for the other samples (made of the same material), a fitted thickness

$$d_{fit} = c\,\tau_{RT}/2 \tag{2}$$

can be obtained for each of the thinner samples. The results are shown in Table I. It is clear that for the thinner samples, d_{fit} is much more accurate than the directly measured thickness d, obtained by the use of a micrometer that can be read to ± 2 μm.

The effective attenuation coefficient α obtained here by plotting the rate of decay of the multiple echoes is due to two causes, namely, the bulk absorption coefficient α_b and the transmission facter s at the sample/transducer interface. For sufficiently small s, we have

$$\alpha = \alpha_b + (s/2d)\ . \tag{3}$$

Equation (3) is intuitively obvious, since α is given by the effective amplitude decrease per unit path length, which is composed of the bulk loss, and the product of the number of arrivals of the sample/transducer interface to make up a unit path length and the

transmission factor out of the sample at each arrival. We found that Eq. (3) can fit most of the values of α in Table I if we take α_b=20 cm^{-1} and s=0.05; in this case, Eq. (3) gives the following values of α in order of increasing thickness: 39.9, 29.8, 23.3, 22.0 and 21.0 cm^{-1}. These fit the effective attenuation coefficients for the four thicker samples to within 8% accuracy. However, the large difference for the thinnest sample (fitted α=39.9 cm^{-1} *versus* observed α=73 cm^{-1}) is suggestive of a much larger value of α_b for the thinnest sample.

In summary, we have made the first demonstration of the opto-acoustic generation and detection of 1 nsec acoustic pulses in condensed matter. These pulses are at least an order of magnitude narrower than those previously reported. The ultra-narrow OA pulses here are generated by N_2 laser pulses of 0.5 nsec duration and detected with thin-film ZnO transducers. The ultra-narrow OA pulses are ideally suited for measuring thickness or acoustic velocity, and acoustic attenuation in thin films by observing the multiple echoes. Accuracy in thickness measurements of 1% is demonstrated for the 12 μm thick stainless steel films once c is known; such high accuracies for thin films of 10 μm thickness is previously impossible with pulsed transducer measurements. We also indicate the measurement of α, which is known to be related to many important thin-film properties like grain size distributions and crystallinity. The measurement of position-dependent ultrasonic absorption by the present short-pulsed OA technique should provide a new imaging tool for characterizing thin film and locating defects. This is especially useful if noncontact techniques[16,17] with fast rise time can be developed to detect the short acoustic pulses on arrival at a sample surface, instead of using thin film transducer as done presently.

ACKNOWLEDGMENTS

This work is supported in part by the Office of Naval Research. The author sincerely thanks H. Coufal for critical reading of this manuscript. He also thanks Professors G. S. Kino and B. T. Khuri-Yakub for letting him use the ZnO transducer.

TABLE I

Summary of results for five samples
of type 302 stainless steel films of different thickness.

Thickness d by micrometer (μm)	Echo round-trip time τ_{RT} (nsec)	Ultrasonic velocity c (10^5 cm/s)	Fitted thickness d_{fit} (μm)	Effective Ultrasonic attenuation α at about 300 MHz (neper/cm)
14(2)	4.24(2)	6.6 (9)	12.57(13)	73
26(2)	8.57(4)	6.1 (5)	25.4 (3)	31
76(2)	25.66(5)	5.9 (2)	76.1 (8)	23.0
128(2)	42.7 (1)	6.00(9)	126.6(13)	23.6
262(2)	88.4 (2)	5.93(6)	(reference)	19.7

REFERENCES

1. Many pulsed OA generation and detection measurements have been reported in the literature. See, for example, references cited in the following reviews: C. K. N. Patel and A. C. Tam, "Pulsed Opto-acoustic Spectroscopy of Condensed Matter," *Rev. Mod. Phys.* **53**, 517 (1981); A. C. Tam and H. Coufal, "Pulsed Opto-acoustics: Theory and Applications," *J. de Physique (Paris) Colloque* **C6**, 9 (1983).
2. A. C. Tam and H. Coufal, *Appl. Phys. Lett.* **42**, 33 (1983).
3. M. Berstein, L. J. Rothberg and K. S. Peters, *Chem. Phys. Lett.* , 215 (1982).
4. J-M. Heritier and A. E. Siegman, *IEEE J. Quant. Elect.* **QE-19** 551 (1983).
5. B. Sullivan and A. C. Tam, *J. Acoust. Soc. Am.* **75**, 437 (1984).
6. W. Imaino and A. C. Tam, *Appl. Opt.* **22**, 1875 (1983).
7. G. S. Kino, D. M. Barnett, N. Grayeli, G. Herrmann, J. B. Hunter, D. B. Ilic, G. C. Johnson, R. B. King, M. P. Scott, J. C. Shyne and C. R. Steele, *J. of Nondestr. Eval.* **1**, 67 (1980).
8. E. P. Papadakis, *J. Acoust. Soc. Am.* **37**, 711 (1965).
9. N. Grayeli, D. B. Ilic, F. Stanke, H. C. Chou and J. C. Shyne, *IEEE 1979 Ultrasonic Symposium Proceedings*, p. 273 (published by IEEE).
10. A. Migliori and T. Hofler, *Rev. Sci. Instr.* **53**, 662 (1982).
11. M. Houze, B. Nongaillard, M. Gazalet, J. M. Rouvaen and C. Bruneel, *J. Appl. Phys.* **55**, 194 (1984).
12. B. T. Khuri-Yakub and G. S. Kino, *Appl. Phys. Lett.* **30**, 78 (1977).
13. C. H. Chou, B. T. Khuri-Yakub, G. S. Kino and A. G. Evans, *J. Nondestr. Eval.* **1**, 235 (1980).
14. W. R. Reynolds and R. L. Smith, *J. Phys. D: Appl. Phys.* **17**, 109 (1984).

15. A. C. Tam and W. P. Leung, to be published.

16. J. E. Bowers, *Appl. Phys. Lett.* **41**, 231 (1982).

17. M. A. Olmstead, N. M. Amer, S. Kohn, D. Fournier and A. C. Boccara, *Appl. Phys. A* **32**, 141 (1983).

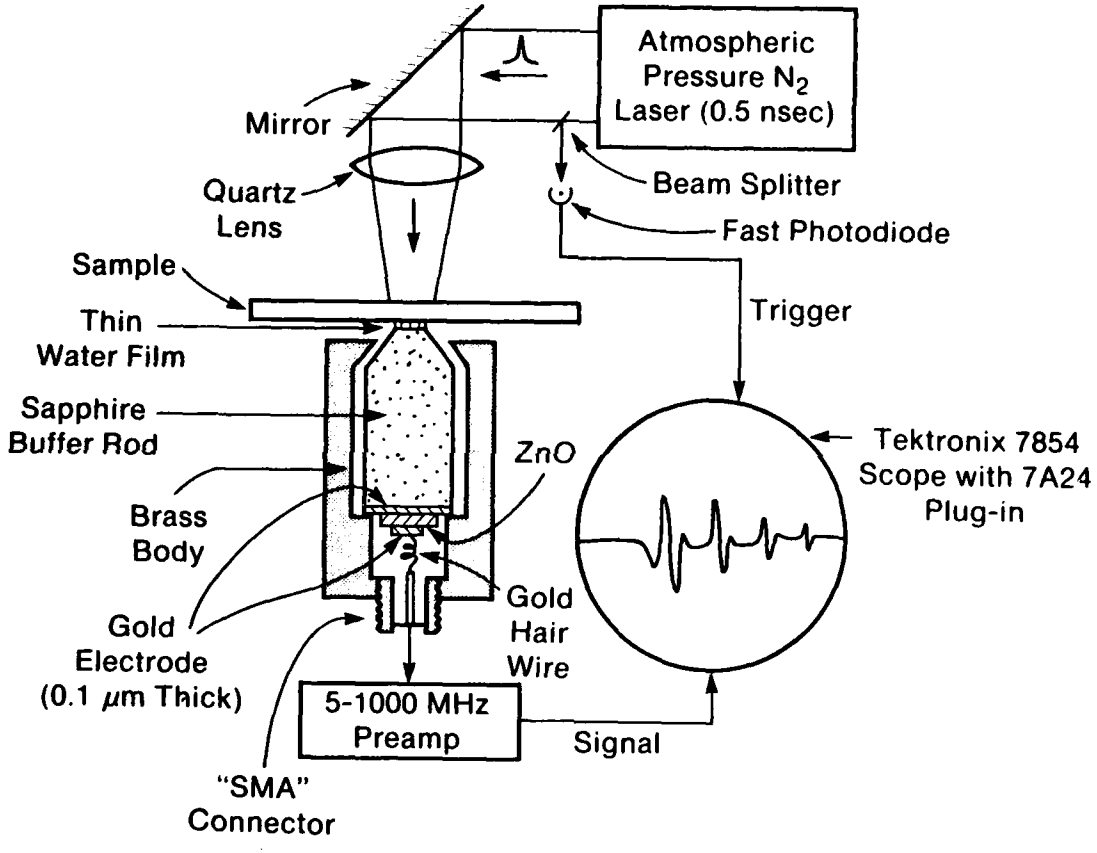


Figure 1. Experimental arrangement (not to scale) to demonstrate OA generation and detection of 1 nsec acoustic pulses in solids.

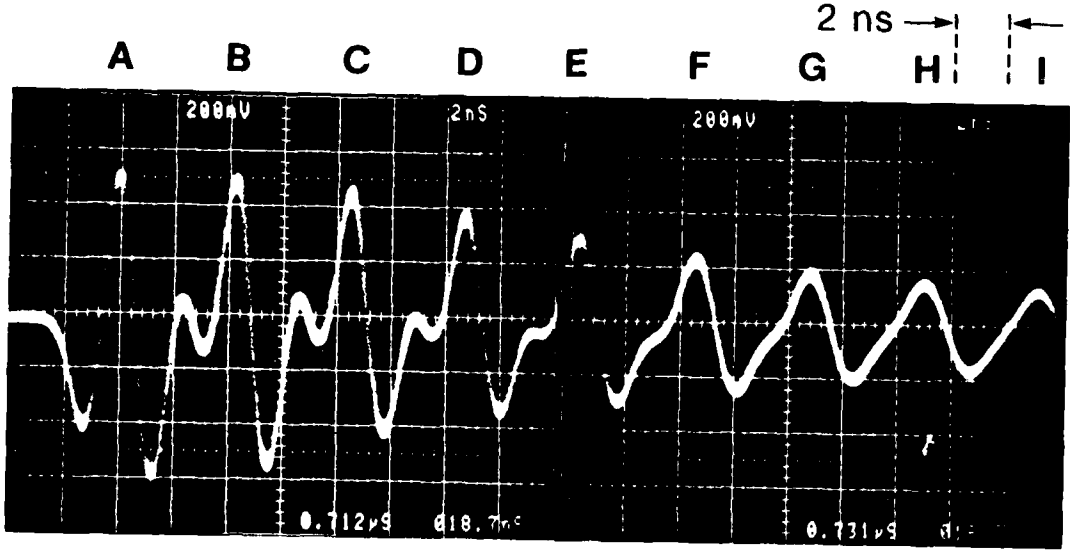


Figure 2. Observed laser-produced acoustic pulse that is multiply reflected in type 302 stainless steel film of thickness d (≈14 μm as measured by micrometer). The first nonreflected pulse A is delayed from the laser firing by 0.892 μsec. Horizontal scale is 2 nsec, division.

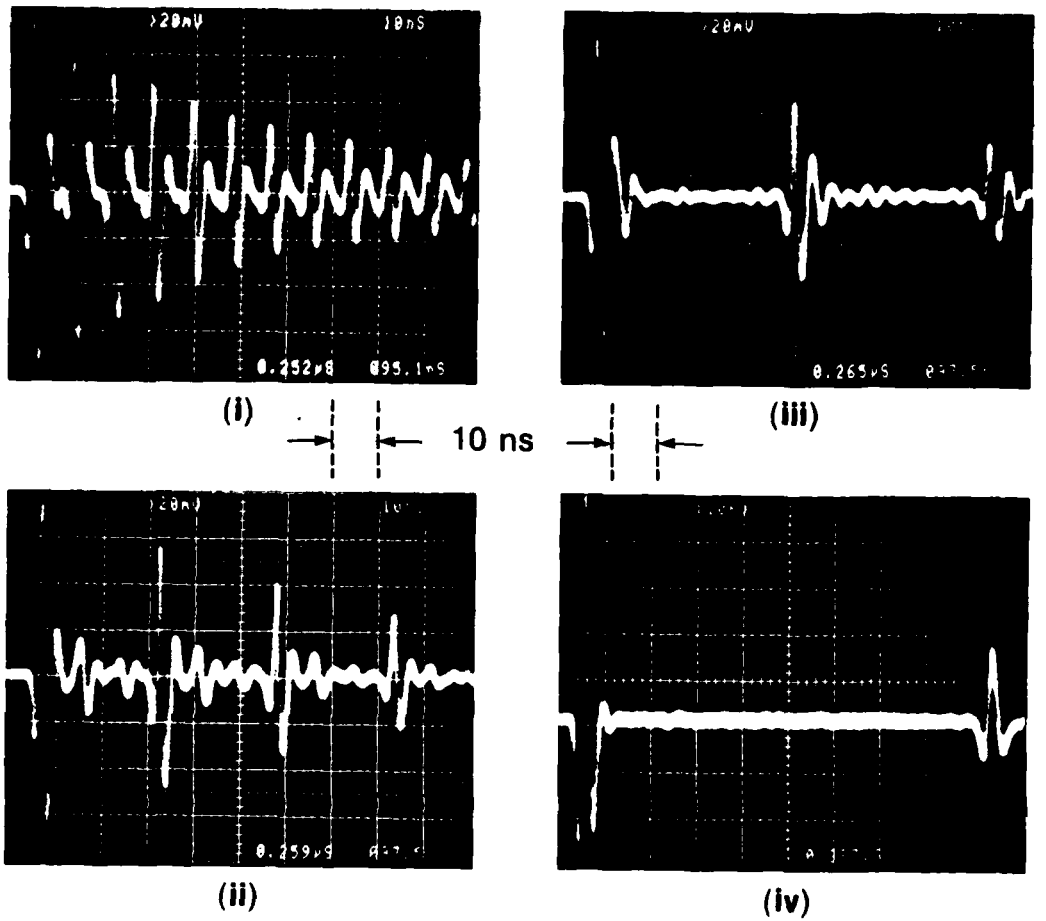


Figure 3. Observed laser-produced acoustic pulses for 302 stainless steel films of thickness d measured by micrometer. (i) d=26 μm; (ii) d=76 μm; (iii) d=128 μm; (iv) d=262 μm. Horizontal scale is 10 nsec per division for all the scope pictures.

DL/413/83/01
GEN/413-2

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies
Office of Naval Research Attn: Code 413 800 N. Quincy Street Arlington, Virginia 22217	2
ONR Pasadena Detachment Attn: Dr. R. J. Marcus 1030 East Green Street Pasadena, California 91106	1
Commander, Naval Air Systems Command Attn: Code 310C (H. Rosenwasser) Washington, D.C. 20360	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko Port Hueneme, California 93401	1
Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12
DTNSRDC Attn: Dr. G. Bosmajian Applied Chemistry Division Annapolis, Maryland 21401	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1
Naval Ocean Systems Center Attn: Technical Library San Diego, California 92152	1
Naval Weapons Center Attn: Dr. A. B. Amster Chemistry Division China Lake, California 93555	1
Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
Dean William Tolles Naval Postgraduate School Monterey, California 93940	1
U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
Mr. Vincent Schaper DTNSRDC Code 2830 Annapolis, Maryland 21402	1
Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Mr. A. M. Anzalone Administrative Librarian PLASTEC/ARRADCOM Bldg 3401 Dover, New Jersey 07801	1

DL/413/83/01
633/413-2

TECHNICAL REPORT DISTRIBUTION LIST, 633

Dr. Henry Freiser
Chemistry Department
University of Arizona
Tucson, Arizona 85721

Dr. Gregory D. Botsaris
Department of Chemical Engineering
Tufts University
Medford, Massachusetts 02155

Dr. J. H. Hargis
Department of Chemistry
Auburn University
Auburn, Alabama 36849

Dr. Andrew Tam
IBM San Jose
5600 Cottle Road
San Jose, California 95193

Dr. Timothy L. Rose
EIC Laboratories, Inc.
111 Chapel Street
Newton, Massachusetts 02158

Dr. Lynn Jarvis
Code 6170
Naval Research Laboratory
Washington, D.C. 20375

Dr. Richard Hollins
Code 385
Naval Weapons Center
China Lake, California 93555

Dr. Christie G. Enke
Department of Chemistry
Michigan State University
East Lansing, Michigan 48824

Dr. Ronald S. Sheinson
Code 6180
Naval Research Laboratory
Washington, D.C. 20375

Dr. Edward J. Poziomek
Chief, Research Division
Chemical Research and
Development Center
ATTN: DRDAR-CLB
Aberdeen Proving Ground, MD 21010

OFFICE OF NAVAL RESEARCH
Contract N00014-83-C-0170
Task No. 633-844

TECHNICAL REPORT No. 8

Pulsed-Laser Generation of Ultra-Short Acoustic Pulses: Application for Thin-Film Ultrasonic Measurements

by

A. C. Tam

IBM Research Laboratory
San Jose, California 95193